algebraic topology exercises

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Homework 1

0 Preliminaries

In the category of sets there is a bijection $\operatorname{Hom}(X \times Y, Z) \cong \operatorname{Hom}(X, \operatorname{Hom}(Y, Z))$ that depends naturally on X, Y and Z. The notions related to this bijection are "Cartesian closed category", "currying" and "internal Hom".

Definition. A category *C* is *Cartesian closed* if:

- 1. C has all finite products (Caveat: some require that C has all finite limits)
- 2. For any object Y the functor $-\times$ Y has a right adjoint, which we will denote by $\operatorname{Map}(Y,-)$ or by $-^Y$.

Remark. By section 3 here, the second property above implies that we get a functor $Map(-,-): C^{op} \times C \to C$, and moreover we get natural isomorphisms $Hom(X, Map(Y, Z)) \cong Hom(X \times Y, Z)$ and $Map(X, Map(Y, Z)) \cong Map(X \times Y, Z)$.

Lemma (Yoneda, wiki). Let F be a functor from a locally small category \mathcal{C} to Set. Then for each object X of \mathcal{C} , the natural transformations Nat(Hom(X, -), F) are in one-to-one correspondence with the elements of F(X), that is

$$Nat(Hom(X, -), F) \cong F(X)$$

Moreover, this isomorphism is natural in A and F when both sides are regarded as functors from $\mathcal{C} \times \mathsf{Set}^{\mathcal{C}}$ to Set. ($\mathsf{Set}^{\mathcal{C}}$ denotes de category of functors from \mathcal{C} to Set.)

There is a contravariant version of Yoneda lemma asserting that if F is a contravariant functor from \mathcal{C} to Set,

$$Nat(Hom(-, X), F) \cong F(X).$$

Corollary. Nat(Hom(-, X), Hom(-, Y)) \cong Hom(X, Y).

Remark. The correspondence $X \mapsto \text{Hom}(-,X)$ is fully faithful, that is, the correspondence $\text{Hom}(X,X') \to \text{Nat}(\text{Hom}(-,X),\text{Hom}(-,X'))$ is injective and bijective.

Exercise (a). Let \mathcal{C} be any category. Show that if for some objects X and X' we have $\operatorname{Hom}(X,Y) \cong \operatorname{Hom}(X',Y)$ for all objects Y, with isomorphisms being natural in Y, then $X \cong X'$. Dually, if $\operatorname{Hom}(Y,X) \cong \operatorname{Hom}(Y,X')$ naturally in Y, then also $X \cong X'$.

Solution. The latter correspondence sends isomorphisms to isomorphisms. Since we are given a natural isomorphism in the problem, we conclude $X \cong X'$. The dual statement follows from the analogue formulation of Yoneda lemma.

Exercise. Let C be a Cartesian closed category and pt be the terminal object. Show that for any object X we have $X \cong Map(pt, X)$.

Solution. Using item (a) with X and X' = Map(pt, X), it suffices to show that

$$Hom(Y, X) \cong Hom(Y, Map(pt, X))$$

for all objects Y and isomorphisms natural in Y.

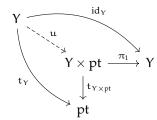
Since *C* is Cartesian closed, we have isomorphisms natural in Y

$$\operatorname{Hom}(Y, \operatorname{Map}(\operatorname{pt}, X)) \cong \operatorname{Hom}(Y \times \operatorname{pt}, X) \cong \operatorname{Hom}(Y, X)$$

since pt is a terminal object. Indeed:

Claim. In a Cartesian closed category C with terminal object pt, we have that $Y \times pt \cong Y$ for any object Y.

Proof of claim. **(From StackExchange)** The universal property of the product $Y \times pt$ shows that the maps id_Y and $t_Y : Y \to pt$ must factor through some $\mathfrak u : Y \to Y \times pt$, making $\pi_1 \circ \mathfrak u = id_Y$.

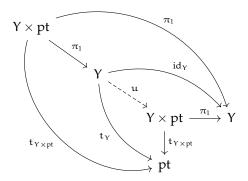


It is also true that $u \circ \pi_1 = id_{Y \times pt}$, since

 $\bullet \ \pi_1 \circ \mathfrak{u} \circ \pi_1 = id_Y \circ \pi_1 = \pi_1 \text{ and }$

• $t_{\mathsf{Y} \times \mathsf{pt}} \circ \mathfrak{u} \circ \pi_1 = t_{\mathsf{Y} \times \mathsf{pt}}$

so by uniqueness of the universal property we get that $u \circ \pi_1 = id_{Y \times pt}$.



1 Based spaces and smash product

[In progress...]

2 Mapping cylinders and Hurewicz cofibrations

Definition (wikipedia). Let X be a topological space and let $A \subset X$. We say that the pair (X,A) has the *homotopy extension property* if for any space Y, any homotopy $g_{\bullet}: A \to Y^{I}$ and any map $\tilde{g}_{0}: X \to Y$ such that $\tilde{g}_{0} \circ \iota = g_{0}$, there exists an *extension* of f_{\bullet} to a homotopy $\tilde{g}_{\bullet}: X \to Y^{I}$ such that $\tilde{g}_{\bullet} \circ \iota = g_{\bullet}$.

$$\begin{array}{ccc}
A & \xrightarrow{g_{\bullet}} & Y^{I} \\
\downarrow & \tilde{g}_{\bullet} & \xrightarrow{\uparrow} & \downarrow \pi_{0} \\
X & \xrightarrow{\tilde{q}_{0}} & Y
\end{array}$$

A *Hurewicz cofibration* is a map $\iota: A \to X$ satisfying the homotopy extension property.

Exercise (a). Prove that an inclusion $f: A \to X$ is a Hurewicz cofibration if and only if $A \times I \cup X \times \{0\}$ is a retract of $X \times I$.

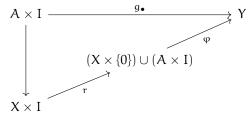
Remark. A little late I noticed the comment on Telegram that we may assume A to be a closed subspace. Maybe I wouldn't have tried the solution following Miller if I had knew this earlier, hehe—still it was nice to see two different solutions.

Solution following Hatcher. (\Longrightarrow) According to the former definition, choose $Y = (X \times \{0\}) \cup (A \times I)$. The inclusion $A \times I \hookrightarrow Y$ is an homotopy g_{\bullet} from A to Y. Also, the inclusion

 $X \times \{0\} \hookrightarrow Y$ is an extension \tilde{g}_{\bullet} . Then there exists an extension \tilde{g}_{\bullet} of the whole homotopy, which is just a map from $X \times I$ to Y. We have thus produced a retraction:

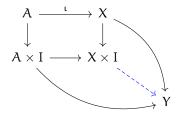
(\Leftarrow) Now suppose that $(X \times \{0\}) \cup (A \times I)$ is a retract of $X \times I$. Let Y be any space, $g_{\bullet} : A \to Y$ an homotopy and \tilde{g}_0 a map such that $\tilde{g}_0 = g_0 \circ f$.

The homotopy g_{\bullet} along with \tilde{g}_0 yield a map $\phi: (A \times I) \cup (X \times \{0\}) \to Y \cup (X \times \{0\})$. The key observation is that if A is closed in X, then this map is continuous by the gluing lemma. Then we simply compose the given retraction r with this map to obtain the homotopy extension:



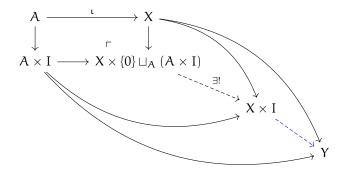
A complicated argument in Hatcher's appendix shows that such a function is continuous even without the assumption that A is closed.

Solution following Miller. The homotopy extension property may be defined as a map $\iota: A \to X$ such that for any solid-arrow diagram as below, a dotted blue arrow exists making the whole diagram commute:



Now consider the pushout corresponding to ι and the inclusion $A \to A \times I$. By the universal property of the pushout, the former diagram must factor by the pushout, and

we get the following diagram:



The implication (\Longrightarrow) of our exercise again follows by choosing $Y = (X \times \{0\}) \cup (A \times I)$. For the implication (\Longleftrightarrow) it appears that we have the same problem as before: we need to construct the blue dashed arrow from the rest of the diagram (using that the black dashed arrow has a left inverse), but it seems that the natural thing to do is defining this function from the two pieces just like before, and we must make sure it is continuous. \Box

Definition. Let $f: X \to Y$ be a map. Let $M_f = X \times [0,1] \cup_f Y$ be the *mapping cylinder of* f, i.e. the pushout of $X \stackrel{\cong}{\to} X \times \{0\} \hookrightarrow X \times [0,1]$ and of $f: X \to Y$. Let $g: X \to M_f$ be the map $X \stackrel{\cong}{\to} X \times \{1\} \to M_f$. Let $h: M_f \to Y$ be the map that is induced by $X \times [0,1] \to Y$: $(x,t) \mapsto f(x)$ and $id_Y: Y \to Y$. Observe that f is the composition of g and h.

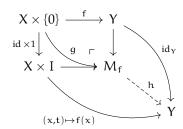
Remark. In both exercises below you might have to use the fact that pushouts are colimits and that colimits commute with products in CGWH, i.e. $(colim A_i) \times B$ is canonically homeomorphic with $colim (A_i \times B)$.

Exercise.

- b. Show that h is a deformation retract, and in particular is a homotopy equivalence.
- c. Show that $g: X \to M_f$ is a cofibration. You may use exercise (a), but the direct proof might be simpler.

Solution.

b. We have that



We must show that there is a homotopy between the identity map on M_f and a retraction from M_f to Y. So we want $h: M_f \times I \to M_f$ such that

$$h(-,0) = id_{M_f}$$
, $img h(-,1) \subset Y$ and $h(-,1)|_Y = id_Y$

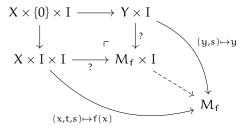
Since M_f is a pullback, we can see it as a colimit, that is

$$M_f = colim(X \times I \leftarrow X \rightarrow Y)$$

and, since colimits commute with products in CGWH, we get

$$M_f \times I = colim(X \times I \times I \leftarrow X \times I \longrightarrow Y \times I)$$

that is,



[I certainly got stuck in concluding...]

c. [Also in progress...] Consider the following lifting problem:

$$\begin{matrix} X \stackrel{H}{\longrightarrow} Z^I \\ g \downarrow & \downarrow^{\pi_0} \\ M_f \stackrel{h}{\longrightarrow} Z \end{matrix}$$

3 Path spaces and fibrations

Exercise.

a. Show that Map(I,Y) deformation retracts on Map(pt,Y). Most likely you'll have to find a correct map $I \times I \to I$. Also show that $Map(I,Y) \to Map(pt,Y)$ is a Hurewicz fibration. The key map will be of the form $I \times I \to I \times I$.

Solution.

a. (Map(I,Y) \rightarrow Map(pt,Y) is a Hurewicz fibration.) Let A be any space. We must show that for any homotopy H and lift h_0 there exists an homotopy \tilde{H} as in the following diagram:

$$\begin{array}{ccc} A \times \{0\} & \xrightarrow{h_0} & Map(I,Y) \\ & & \downarrow & \downarrow p \\ A \times I & \xrightarrow{H} & Map(0,Y) \end{array}$$

From the isomorphism $Map(X \times Y, Z) \cong Map(X, Map(Y, Z))$ we may rewrite the problem as

$$(A \times \{0\}) \times I$$

$$(A \times I) \times I \xrightarrow{\tilde{H}} Y$$

$$(A \times I) \times \{0\}$$

So we define the dashed arrow by

$$(\mathfrak{a}, \mathfrak{s}, \mathfrak{t}) \mapsto egin{cases} \mathsf{H}_0(\mathfrak{a}, 0, \mathfrak{s} - \mathfrak{t}) & \text{when } \mathfrak{s} - \mathfrak{t} \geqslant 0 \\ \mathsf{H}(\mathfrak{a}, \mathfrak{t} - \mathfrak{s}, 0) & \text{when } \mathfrak{s} - \mathfrak{t} \leqslant 0 \end{cases}$$

so that when s=t the functions coincide, when s=0 we get H and when t=0 we get H_0 .

(Map(I, Y) **deformation retracts on** Map(pt, Y)**.)** We must show there is a homotopy

$$h: Map(I, Y) \times I \longrightarrow Map(I, Y)$$

such that

$$h(-,0) = id_{Map(I,Y)}, \qquad h(-,1) \subset Map(pt,Y)$$

and
$$h(-,1)|_{Map(pt,Y)} = id_{Map(pt,Y)}$$
.

Consider the map

$$I \times I \rightarrow I$$

 $(s,t) \mapsto s - st$

Our deformation retract may be written like

$$h: Map(I,Y) \times I \longrightarrow Map(I,Y)$$

$$(f(s),t) \longmapsto f(s-st)$$

Then for t = 0 we have the identity on Map(I, Y), and when t = 1 we have ev_0 .

Let $f: X \to Y$ be a map. Let E_f be the pullback of $f: X \to Y$ and of $ev_0: Map(I,Y) \to Y$. Let $h: X \to E_f$ be the map that sends x to (x, const(f(x))), where $const(f(x)): I \to Y$ is the constant path at f(x). Let $g: E_f \to Y$ be the composition of projection map $E_f \to Map(I,Y)$ with $ev_1: Map(I,Y) \to Y$.

Homework 1.5

1 Exercise on model categories

Exercise (3.1.8 from Riehl). Verify that the class of morphisms \mathcal{L} characterized by the left lifting property against a fixed class of morphisms \mathcal{R} is closed under coproducts, closed under retracts, and contains the isomorphisms.

Solution. (Coproducts.) Suppose the maps $\ell_i : A_i \to B_i$ are in \mathcal{L} . Then their coproduct in the arrow category is the obvious map $\coprod A_i \to \coprod B_i$.

Explicitly, their coproduct is an arrow $\coprod \ell_i$ and a collection of maps $f_i : \ell_i \to \coprod \ell_i$ such that for any other object $m : A \to B$ in the arrow category and a map $g : \ell \to m$, the following diagram is completed uniquely:

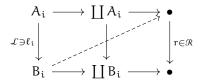
$$\ell_i \xrightarrow{f_i} \coprod \ell_i \xrightarrow{\exists !} \mathfrak{m} \quad \forall i$$

So we conclude that the source of $\coprod \ell_i$ is $\coprod A_i$ and its target $\coprod B_i$. Indeed, we really looking at

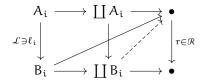
$$\begin{array}{ccc} A_{i} & \stackrel{\ell_{i}}{\longrightarrow} & B_{i} \\ f_{i}^{1} \downarrow & & \downarrow f_{i}^{2} \\ \coprod A_{i} & \stackrel{\coprod \ell_{i}}{\longrightarrow} & \coprod B_{i} \\ \exists ! \downarrow & & \downarrow \exists ! \\ A & \stackrel{}{\longrightarrow} & B \end{array}$$

Now consider the following lifting problem with respect to a morphism $r \in \mathcal{R}$:

Since $\ell_i \in \mathcal{L}$, we have maps



which in turn means we have a unique map



by the universal property of the coproduct $\coprod B_i$.

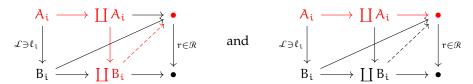
To conclude we need to check that the triangles below and above the dashed arrow in the former diagram commute. This follows from the universal property of the coproducts $\coprod A_i$ and $\coprod B_i$ since, in general,

$$\text{Hom}\left(\coprod X_{i},Y\right)\cong\prod\text{Hom}(X_{i},Y).$$

More explicitly, we now that the red paths in the following diagrams are the same:

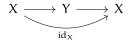


and also

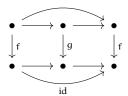


so the conclusion follows from the former comment.

(Closed under retracts.) Let us at least state what a retract of a morphism g should be in the arrow category. Recall that a retract is just



So in the arrow category we get



2 Hatcher's exercise on Whitehead's theorem

Theorem 1 (Whitehead, May). If X is a CW complex and $e: Y \to Z$ is an n-equivalence, then $e_*: [X, Y] \to [X, Z]$ is a bijection if dim X < n and surjection if dim X = n.

Theorem 2 (Whitehead, May). An n-equivalence between CW complexes of dimension less than n is a homotopy equivalence. A weak equivalence between CW complexes is a homotopy equivalence.

Theorem 3 (Whitehead (4.5), Hatcher). If a map $f: X \to Y$ between connected CW complexes induces isomorphisms $f_*: \pi_n(X) \to \pi_n(Y)$ for all n, then f is a homotopy equivalence. In case f is the inclusion of a subcomplex $X \hookrightarrow Y$, the conclusion is stronger: X is a deformation retract of Y.

Exercise (Hatcher 4.1.12). Show that an n-connected, n-dimensional CW complex is contractible.

Solution. Just recall that n-connectedness means that $\pi_i(X)=0$ for all $i\leqslant n$, which means that X is contractible by theorem 2.

Homework 2

Exercise (4.1.3). For an H–space (X, x_0) with multiplication $\mu : X \times X \to X$, show that the group operation in $\pi_n(X, x_0)$ can also be defined by the rule $(f + g)(x) = \mu(f(x), g(x))$.

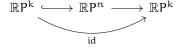
Exercise (4.1.19). Consider the equivalence relation \simeq_w generated by weak homotopy equivalence: $X \simeq_w Y$ if there are spaces $X = X_1, X_2, \ldots, X_n = Y$ with weak homotopy equivalences $X_i \to X_{i+1}$ or $X_i \leftarrow X_{i+1}$ for each i. Show that $X \simeq_w Y$ iff X and Y have a common CW approximation.

Solution. (\iff) Suppose Z is a common CW approximation of X and Y, that is, Z is a CW complex and there are weak homotopy equivalences $Z \to X$ and $Z \to Y$. Then the sequence of spaces $X = X_1$, $Z = X_2$ and $Y = X_3$ shows that $X \simeq_w Y$.

(\Longrightarrow) Suppose Z is a CW approximation of X and let's show it can be made (somehow) into a CW approximation of Y. There is a weak homotopy equivalence Z \to X, and also a weak homotopy equivalence either X = $X_1 \to X_2$ or X = $X_1 \leftarrow X_2$. I wonder if this implies that the composition Z \to X = $X_1 \to X_2$ is also a weak homotopy equivalence \Box

Exercise (4.2.1). Use homotopy groups to show that there is no retraction $\mathbb{R}P^n \to \mathbb{R}P^k$ for n > k > 0.

Solution (in progress...) Suppose there is a retraction



it induces isomorphisms

$$\pi_i(\mathbb{R}P^k) \longrightarrow \pi_i(\mathbb{R}P^n) \longrightarrow \pi_i(\mathbb{R}P^k)$$

If we had that this is a Serre fibration, we would get that

content...

Exercise (4.2.13). Show that a map between connected n-dimensional CW complexes is a homotopy equivalence if it induces an isomorphism on π_i for $i \leq n$. [Pass to universal covers and use homology.]

Solution. Let X and Y be n-dimensional CW complexes and $f: X \to Y$ such that $f_*:$ $\pi_i(X) \to \pi_i(Y)$ is an isomorphism for $i \leq n$. Let's try to use Hurewicz theorem, which states that a map between simply connected CW complexes is a homotopy equivalence if it induces isomorphisms on all homology groups.

Consider the universal covers \tilde{X} and \tilde{Y} , which are simply connected and also have CW structures. By prop. 4.1, the cover projections induce isomorphisms in the homotopy groups for all $i \ge 2$. By StackExchange there is a unique lift \tilde{f} to the universal covers making the diagram on the left commute, and by functoriality the diagram on the right also commutes.

We conclude that \tilde{f} is a weak homotopy equivalence, and by prop. 4.21 it induces isomorphisms on homology groups. Finally, by Hurewicz theorem (coro. 4.33) it is an homotopy equivalence and so is f. \Box

Exercise. There is a fiber sequence $U(n) \hookrightarrow U(n+1) \to U(n+1)/U(n) \cong S^{2n+1}$. Use this to show that $\pi_k(U(n)) \to \pi_k(U(n+1))$ is isomorphism for n > k/2. Compute $\pi_k(U(n))$ for $n \ge 2$ and k = 1, 2, 3. In fact, if k is even then $\pi_k(U(N)) = 0$ and if k is odd then $\pi_k(U(N)) = \mathbb{Z}$, where again N > k/2. These equalities are known as Bott periodicity.

Solution. The required isomorphisms $\pi_k(U(n)) \to \pi_k(U(n+1))$ follow simply from the fact that S^{2n+1} is 2n + 1-connected: in the long homotopy sequence of the fiber bundle we have

$$\pi_{k+1}(S^{2n+1}) \, \longrightarrow \, \pi_k(U(n)) \, \longrightarrow \, \pi_k(U(n+1)) \, \longrightarrow \, \pi_k(S^{2n+1})$$

so when $2n + 1 > k + 1 \iff n > k/2$ the homotopy groups of the spheres vanish and we have an isomorphism.

The group $\pi_1(U(n))$ is isomorphic to \mathbb{Z} . This follows from the fact that U(1) is homeomorphic to a circle and by induction using the former isomorphism $\pi_1(U(n)) \cong \pi_1(U(n+1))$. We also have $\pi_2(U(1)) = 0$, so that again by induction we get $\pi_2(U(n)) = 0$. Finally, a similar argument shows $\pi_3(U(n)) = 0$.

Exercise (4.2.32). Show that if $S^k \to S^m \to S^n$ is a fiber bundle, then k = n - 1 and m = 2n - 1. [Look at the long exact sequence of homotopy groups.]

Solution (in progress...) The sequence of homotopy groups is

$$\cdots \to \pi_i(S^k) \to \pi_i(S^m) \to \pi_i(S^n) \to \pi_{i-1}(S^k) \to \pi_{i-1}(S^m) \to \cdots$$

so that if $i \leq k$ we have $\pi_i(S^m) = \pi_i(S^n)$,

cohomology ring of $\mathbb{C}P^n$

Exercise. Show that

$$H^{\bullet}(\mathbb{C}P^n) \cong \mathbb{Z}[\alpha]/(\alpha^{n+1})$$

where α has degree 2.

Proof. The CW structure of $\mathbb{C}P^n$ consists of one cell for every even dimension. This gives us the following chain complex:

$$\mathbb{Z} \longrightarrow 0 \longrightarrow \mathbb{Z} \longrightarrow \dots \longrightarrow \mathbb{Z}$$
, if n is even

$$\mathbb{Z} \longrightarrow 0 \longrightarrow \mathbb{Z} \longrightarrow \dots \longrightarrow 0$$
, if n is odd

which yields the cohomology

$$H^{i}(\mathbb{C}P^{n}) = \begin{cases} \mathbb{Z}, & i = 0, 2, 4, \dots 2n \\ 0, & i \text{ otherwise} \end{cases}$$

so that

$$H^{\bullet}(\mathbb{C}P^{n}) = H^{0}(\mathbb{C}P^{n}) \oplus H^{2}(\mathbb{C}P^{n}) \oplus \ldots \oplus H^{2n}(\mathbb{C}P^{n})$$

This means that the underlying group of the cohomology ring is the same as that of

$$\mathbb{Z}[\alpha]/(\alpha^{n+1})$$

where α has degree 2. To show that these groups are also isomorphic as algebras we can use Poincaré duality as follows.

Consider the case n = 2, where we may immediately multiply the generator of second cohomology group with itself:

$$\begin{split} H^2(\mathbb{C}P^2) \times H^2(\mathbb{C}P^2) &\to H^4(\mathbb{C}P^2) \\ (\alpha,\alpha) &\mapsto \alpha \smile \alpha = \alpha^2 \end{split}$$

By Poincaré duality this map is bilinear, so it must map generator to a generator. The fact that the product of the generator in degree 2 is the generator of degree 4 yields an homomorphism

$$\begin{split} \phi: \mathbb{Z}[\alpha] &\to H^{\bullet}(\mathbb{C}P^n) \\ \alpha &\mapsto \alpha \in H^2(\mathbb{C}P^n) \end{split}$$

with kernel (α^{n+1}) as desired.

Now the case of $\mathbb{C}P^3$ is:

$$\begin{split} H^2(\mathbb{C}P^3) \times H^4(\mathbb{C}P^3) &\to H^6(\mathbb{C}P^3) \\ (\alpha,\alpha^2) &\mapsto \alpha \smile \alpha^2 = \alpha^3 \end{split}$$

which also maps generator to generator, producing the desired algebra isomorphism. Notice we have used the group isomorphism $H^4(\mathbb{C}P^3) \approx H^4(\mathbb{C}P^2)$ when denoting the generator of $H^4(\mathbb{C}P^3)$ as α^2 . Such an isomorphism is induced by inclusion $\mathbb{C}P^{n-1} \hookrightarrow \mathbb{C}P^n$ via relative cohomology exact sequence.

The case for dimension n follows by induction.

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